Original Contribution

Imaging Characteristics of Ischemic Strokes Related to Patent Foramen Ovale

Bum Joon Kim, MD; Hoyon Sohn, MD; Byung Joo Sun, MD; Jae-Kwan Song, MD; Dong-Wha Kang, MD; Jong S. Kim, MD; Sun U. Kwon, MD

Background and Purpose—Subclinical atrial fibrillation (AF) and patent foramen ovale (PFO) are the major causes of cryptogenic stroke, and neuroimaging may help distinguish the cause. We compared the imaging characteristics of ischemic stroke caused by PFO (PFO-stroke) and AF (AF-stroke).

Methods—We recruited 117 patients with PFO-stroke and 358 patients with AF-stroke after excluding other causes. The lesion patterns were classified according to number, location, size, and pertinent vascular territory and were compared between the 2 groups. Occlusion of the corresponding artery and its recanalization rate were also investigated.

Results—The lesion pattern of a PFO-stroke was more frequently observed as a single cortical infarction (34.2% versus 3.1%; P<0.001) or multiple small (<15 mm) scattered lesions (23.1% versus 5.9%; P<0.001) and in the vertebrobasilar artery territory (44.4% versus 22.9%; P<0.001). By contrast, AF-stroke was more frequently observed as a large corticocortical infarction or confluent lesion (>15 mm) with additional lesions in multirculatory territories. For a PFO-stroke, occlusion of the corresponding vessel on angiography was less frequent (34.2% versus 71.5%; P<0.001), and the neurological deficit evaluated by the National Institutes of Health Stroke Scale was mild (3.48±4.16 versus 9.15±7.35; P<0.001). The recanalization rate was also lower (57.1% versus 78.3%; P=0.007).

Conclusions—A PFO-stroke usually appears as a single cortical or multiple small ischemic lesions in the vertebrobasilar circulation without any visible vessel occlusion on angiography. The recanalization rate is significantly lower than in AF-stroke. These imaging characteristics of PFO-stroke may help to diagnose the mechanism and determine the treatment strategy. (Stroke. 2013;44:00-00.)

Key Words: atrial fibrillation • foramen ovale, patent • stroke

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despite progress in diagnostic evaluations, 40% of all strokes still remain cryptogenic. It is now believed that more than half of all cryptogenic strokes are cardioembolic in origin.1 Advanced cardiology workups using autotriggered atrial fibrillation (AF) devices2 or implanted cardiac monitors3 demonstrate a high prevalence of subclinical AF in patients with stroke. However, these monitoring devices require a relatively long detection period of several months from the onset of stroke. Patent foramen ovale (PFO) is another important cause of cryptogenic stroke. The detection of PFO is usually confirmed by transesophageal echocardiography (TEE). However, this technique is semi-invasive and may cause discomfort in patients, thus requiring sedation.

Early determination of the causative factors of cryptogenic stroke is essential for secondary prevention. Ischemic strokes caused by subclinical AF may need anticoagulation therapy, whereas PFO-associated strokes (PFO-stroke) may benefit from deploying closure devices. Neuroimaging may help distinguish the cause of stroke. Ischemic lesions presented on diffusion-weighted image (DWI) are known to be different according to the stroke mechanisms. Therefore, the different mechanisms of emboli formation in PFO- and AF-stroke may account for some of these differences.

In this study, we aimed to investigate the characteristics of PFO-stroke by its DWI lesion pattern, obstruction of corresponding vessels, and recanalization rate and compared it with AF-associated stroke (AF-stroke).

Methods

Patients

We retrospectively reviewed patients with acute ischemic stroke (within 2 weeks of the onset of symptoms) who were admitted to the Asan Medical Center between January 2005 and April 2011. Patients classified as “undetermined etiology—negative” according to TOAST (Trial of Org 10172 in Acute Stroke Treatment) classification or highly suspicious of cryptogenic embolic source were defined as cryptogenic stroke. Among them, patients who received both
DWI and magnetic resonance angiography (MRA) were selectively enrolled. Patients with acute ischemic lesions on DWI and PFO documented by TEE were included in the PFO-stroke group. However, patients with potential coexisting embolic sources such as: (1) evidence of significant atherosclerosis in corresponding arteries, evaluated by MRA, or in the aortic arch evaluated by TEE; (2) high-risk cardiac arrhythmias according to the results of 24-hour Holter or continuous electrocardiography monitoring; or (3) evidence of other causes of ischemic stroke, such as arterial dissection, vasculitis, or small vessel occlusion, were excluded from the study. In the AF-stroke group, patients with acute ischemic stroke previously diagnosed with AF or newly detected after admission were included. Other potential cardiac sources and large artery atherosclerosis were excluded in the same manner in the PFO-stroke group. This study was approved by the institutional review board of our center. Informed consent was not obtained because of the retrospective nature of the study.

Clinical Data and Diagnosis of PFO
Demographic characteristics, vascular risk factors, concurrent medications, baseline laboratory results on the day of admission (blood cell counts, lipid profiles, glucose, blood urea nitrogen, creatinine, C-reactive protein, and prothrombin time—international normalization ratio [PT-INR]), and thrombolysis data were obtained from the prospectively acquired stroke database. The severity of neurological deficits was evaluated according to the National Institutes of Health Stroke Scale at admission and discharge. TEE, a gold standard for the diagnosis of intrasplantal disease, was used for the evaluation of PFO. It was performed within 2 weeks of the onset of symptoms. The detection of PFO was done by a previously reported method. In brief, hand-agitated saline with microbubbles was administered through the right antecubital vein at rest and during the Valsalva maneuver. PFO was defined as the passage of >3 microbubbles from the right to the left atrium through the gap within 3 cardiac cycles after complete opacification of the right atrium. PFO size and the coexistence of an atrial septal aneurysm or hypermobile septum were measured. The size of PFO was measured at multiple planes, and the maximal length between septum primum and secundum at resting or during Valsalva was accepted. Atrial septal aneurysm or hypermobile septum was defined as >10 mm of phasic septal excursion into the atrium or a sum total excursion of ≥15 mm during the cardiorespiratory cycle with base ≥15 mm, measured from M-mode. PFO >2 mm in diameter combined with or without atrial septal aneurysm or hypermobile septum was regarded as medium- or high-risk PFO, respectively. The TEE data were reviewed by a cardiologist (B.J.S.) blinded to all the clinical information.

Imaging Study
DWI, time-of-flight MRA (for the evaluation of intracranial arteries), and contrast-enhanced MRA (for extracranial arteries) were conducted within 2 weeks of the onset of symptoms. DWI and MRA results were mandatory for enrollment in the study to confirm an ischemic lesion and to exclude other causes of embolization, respectively. Follow-up MRA was performed a week after the initial scan to assess recanalization.

The DWI lesions were analyzed by pattern and location. The lesion patterns were investigated according to number, distribution, and size. They were divided into single or multiple lesions according to the number of ischemic lesions. Single lesions were then classified into cortical, subcortical, and cortico-subcortical lesions according to their distribution. Subcortical lesions were also divided by their size with a cutoff value of 15 mm. Multiple lesions were classified as multiple small (<15 mm) scattered lesions, confluent lesion (>15 mm) with additional small lesions, and multiple lesions in various vascular territories. Each lesion pattern was also analyzed according to lesion location (supratenorial lesion, infratentorial lesion, and lesions in both supra- and infratentorial). The pertinent vascular territory of ischemic lesions was classified into right carotid circulation, left carotid circulation, vertebralbasilar circulation, and multicirculatory. The vessel supplying the vascular territory of the ischemic lesion was regarded as the corresponding vessel. Angiographic findings were classified according to the size of the corresponding vessels that were completely occluded: (1) extracranial large vessels: common carotid artery, proximal internal carotid artery, and proximal vertebral artery; (2) intracranial main vessels: distal internal carotid artery, distal vertebral artery, middle cerebral artery, and basilar artery; (3) intracranial branching vessels: anterior and posterior cerebral artery, branches of the middle cerebral artery, and superior cerebellar artery; and (4) no visible occlusion on MRA. Two investigators (H.S. and B.I.K.), blinded to the patient’s clinical information, evaluated the results of the imaging studies. If any discrepancies were encountered, a third investigator was consulted to resolve the issue.

Statistical Analysis
The demographics, risk factors, laboratory results, and National Institutes of Health Stroke Scale were compared between patients with PFO-stroke and AF-stroke. The lesion pattern, angiographic findings, pertinent vascular territory of the lesion, and recanalization rate were also compared. Pearson χ² test, Student t test, and Mann–Whitney U test were appropriately used. Because the angiographic findings represent the size of the embolus indirectly and have an ordinal nature, linear to linear association by χ² test was also performed for trend analysis. Multivariate binary logistic regression was performed to investigate the independent association between PFO-stroke and recanalization. Factors related to recanalization (PT-INR, thrombolysis, size of obstructed corresponding vessel, and PFO versus AF) were entered. Statistical analyses were performed using SPSS for Windows version 17.0 (SPSS Inc; Chicago, IL).

Results
During the study period, 7491 patients were admitted to our center because of ischemic stroke, of whom 1132 patients (15.1%) were classified as cryptogenic stroke. Among them,
1065 patients (94.1%) received TEE. PFO was observed in 191 (17.9%) patients, according to the previous definition. Seventy-four patients were excluded from the study because they did not meet the previously outlined criteria. For AF-stroke, 442 patients had AF, and 84 patients were excluded because of coexisting potential stroke mechanisms or insufficient data. Finally, 117 patients with PFO-stroke and 358 patients with AF-stroke were included (Figure 1). PFO was >2 mm in diameter in 51 patients (42.1%), and atrial septal aneurysms or hypermobile septa were observed in 36 patients (30.8%). Thirty-six patients (30.0%) were classified as medium-risk PFO, and 25 patients (20.8%) were classified as high risk.

Clinical and Laboratory Characteristics
Compared with AF-stroke, patients with PFO-stroke were young and the proportion of males was higher. Conventional risk factors such as hypertension, hyperlipidemia, and previous history of stroke were less often associated with PFO-stroke, whereas smoking was more often associated with PFO-stroke. National Institutes of Health Stroke Scale was significantly lower in patients with PFO-stroke at baseline and follow-up (3.48±4.16 versus 9.15±7.35 and 2.30±3.32 versus 8.19±9.84, respectively; P<0.001). According to the results of the laboratory data, platelet counts (222±54 versus 205±63; P=0.009) and fibrinogen levels (300±60 versus 271±72; P<0.001) were higher in patients with PFO-stroke, whereas blood urea nitrogen and C-reactive protein were higher in patients with AF-stroke. PFO-stroke patients received less thrombolysis or previous anticoagulation therapy. However, the mean values of PT-INR in both groups were within the normal range, and subjects on adequate anticoagulation therapy (PT-INR>1.7) were not statistically different between the 2 groups (Table 1).

Imaging Characteristics
Representative cases of each lesion pattern are presented in Figure 2. PFO-stroke was more frequently observed as a single cortical lesion (34.2% versus 3.1%; P<0.001) or multiple small scattered lesions (23.1% versus 5.9%; P<0.001) and occurred more frequently in the vertebrobasilar circulation (44.4% versus 22.9%; P<0.001). However, large cortico-subcortical lesions, confluent large lesions with additional lesions, or multicirculatory infarctions were more frequently observed in patients with AF-stroke. PFO-stroke patients received less thrombolysis or previous anticoagulation therapy. However, the mean values of PT-INR in both groups were within the normal range, and subjects on adequate anticoagulation therapy (PT-INR>1.7) were not statistically different between the 2 groups (Table 1).
in 57.1% (20 of 35 patients) of PFO-stroke cases, and the recanalization rate of AF-stroke was higher (78.3% [167 of 212 patients]; \( P=0.007 \); Table 2). Multivariate analysis demonstrated that thrombolysis and obstruction of small vessels were independently associated with recanalization (\( P=0.002; P=0.003 \), respectively). However, PFO-stroke was independently associated with poor recanalization after adjusting for potential confounders (\( P=0.023 \); Table 3).

Figure 2. Comparison of patent foramen ovale–associated stroke (PFO-stroke) and atrial fibrillation–associated stroke (AF-stroke). Representative cases showing differences in ischemic lesion patterns, angiographic findings, and the vascular territory of ischemic lesions between PFO-stroke and AF-stroke. Arrows indicate ischemic lesions or occluded vessels.
The aim of this study was to compare the imaging characteristics of ischemic lesions and the recanalization rate in PFO-stroke and AF-stroke. Our results showed that PFO-strokes were more likely to present as a single cortical lesion or multiple small scattered lesions, more often located in the vertebrobasilar circulation. Occlusion of the corresponding artery was less frequent, and the recanalization rate was lower than in AF-stroke. Formation of a thrombus in the venous system precedes a paradoxical embolism, which is considered a major mechanism of PFO-stroke. Therefore, thrombogenic conditions are usually required. AF-stroke was associated with all of the conventional risk factors of stroke except smoking, which was more frequently observed in PFO-strokes. Smoking increases blood viscosity by elevating fibrinogen and hematocrit levels. It may also damage the endothelium and cause thrombosis.

### Table 2. Distribution of Ischemic Lesion Patterns in the Supratentorial and Infratentorial Area

<table>
<thead>
<tr>
<th></th>
<th>Single Lesion</th>
<th>Multiple Lesions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cortico-</td>
<td>Cortical</td>
</tr>
<tr>
<td>PFO-stroke Supratentorial</td>
<td>10 (12.8)</td>
<td>30 (38.5)</td>
</tr>
<tr>
<td>Infratentorial</td>
<td>16 (45.7)</td>
<td>10 (28.6)</td>
</tr>
<tr>
<td>Both</td>
<td>3 (75.0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Total</td>
<td>26 (22.2)</td>
<td>40 (34.2)</td>
</tr>
<tr>
<td>AF-stroke Supratentorial</td>
<td>137 (47.4)</td>
<td>10 (3.5)</td>
</tr>
<tr>
<td>Infratentorial</td>
<td>28 (56.0)</td>
<td>1 (2.0)</td>
</tr>
<tr>
<td>Both</td>
<td>1 (5.3)</td>
<td>8 (42.1)</td>
</tr>
<tr>
<td>Total</td>
<td>165 (46.1)</td>
<td>11 (3.1)</td>
</tr>
</tbody>
</table>

Values are expressed as numbers and percentages (raw). AF-stroke indicates atrial fibrillation–associated stroke; and PFO-stroke, patent foramen ovale–associated stroke.

### Discussion

The aim of this study was to compare the imaging characteristics of ischemic lesions and the recanalization rate in PFO-stroke and AF-stroke. Our results showed that PFO-strokes were more likely to present as a single cortical lesion or multiple small scattered lesions, more often located in the vertebrobasilar circulation. Occlusion of the corresponding artery was less frequent, and the recanalization rate was lower than in AF-stroke.
Therefore, smoking and elevated fibrinogen are associated with venous thromboembolism.8,9 In our study, although hematocrit levels were not significantly different between the 2 groups, fibrinogen and platelet counts were significantly higher in patients with PFO-stroke, even after adjusting for smoking. High platelet counts are associated with venous thromboembolism in specific groups of patients.10,11 However, only 2 subjects among the enrolled patients demonstrated thrombocytosis (>450,000/mm³), and the mean value of platelet counts in both groups were within the normal range (Table 1). Therefore, the clinical significance of differences in platelet counts should be interpreted cautiously.

PFOs may work as filters, allowing only smaller emboli to pass through the shunt. This explains why: (1) ischemic lesions presented as small cortical embolic infarctions or multiple small scattered lesions; (2) the incidence of corresponding vessel obstruction was low; and (3) the neurological deficit was milder in patients with PFO-stroke than in patients with AF-stroke in our results. From a previous study, a right-to-left shunt was more frequently observed from small infarcts in cryptogenic stroke, and therefore, mechanisms other than paradoxical embolism were suggested to play an important role in patients with large cryptogenic stroke.12 A recent study demonstrated that PFO-stroke is superficially located and larger than other cryptogenic causes.13 The superficial location of lesions was consistent with our findings. In our study, patients without MRA were excluded, and a high portion of cryptogenic patients received extensive heart workups. We have tried to evaluate the mechanism of stroke comprehensively and excluded PFO-stroke with other possible causes of stroke.

A study using radionuclide venography revealed excess flow to the vertebrobasilar circulation after the Valsalva maneuver in patients with PFO.14 Because paradoxical embolism also needs the right-to-left shunt to be opened by the Valsalva maneuver, the increased blood flow to the pertinent territory after the maneuver may explain the high incidence of ischemic lesions in the vertebrobasilar circulation in PFO-stroke. Vertebrobasilar circulation receives less adrenergic innervation.15 Therefore, this territory is also more prone to hypertensive encephalopathy.16 When the sympathetic tone is increased by the Valsalva maneuver, vertebrobasilar circulation, which is less responsive to sympathetic stimuli, increases blood flow. This may increase the chance of blood clot formation after increased blood flow to the vertebrobasilar circulation after passage through PFO. However, the exact mechanism should be investigated further. Interestingly, cortico-subcortical lesion patterns were frequently observed in the infratentorial lesions of PFO-stroke. This may be associated with the relatively small orifice and long passage of cerebellar arteries.

Both PFO-stroke and AF-stroke demonstrated a high recanalization rate attributable to the fibrin-rich composition of clots, and it was lower in PFO-stroke. Although the thrombolysis rate was higher in AF-stroke, PFO was still related to poor recanalization after adjusting for the level of PT-INR, thrombolysis, and angiographic findings, which indirectly represent the size of embolus. An embolus formed in the venous system floats a long distance after initial thrombosis and becomes organized, mature, and firm compared with the fresh clot caused by AF. These firm emboli may be resistant to recanalization. In addition, a tunnel length >1 cm was associated with PFO-stroke, and in-tunnel thrombosis may also contribute to the pathomechanism of PFO-stroke.17 Long tunnels could represent sites for thrombus formation because of turbulent flow inside the tunnel. These various pathomechanisms on thrombus formation in PFO may influence the recanalization rate of PFO-stroke.

There are some noteworthy limitations to this study. First, this was a retrospective study. Because we included patients capable of receiving TEE, subjects with poor clinical conditions may have been excluded, which may have caused a selection bias. Second, the prevalence of PFO was lower than the previous studies. However, Asian ethnicity18 and old age19 of the study population may help explain the relatively low rate of PFO in patients with cryptogenic stroke. Third, as mentioned previously, the low proportion of PFO-stroke patients receiving thrombolysis or previous anticoagulation, may have influenced the recanalization rate. Therefore, we performed a multivariate analysis, and the results demonstrated that PFO-stroke was still independently associated with lower recanalization rates. Fourth, the diagnostic workup for the venous thrombosis, which caused paradoxical embolisms, was not fully investigated. Identifying the comorbid conditions, including deep vein thrombosis, hypercoagulability, and underlying malignancy, may have strengthened our results. Last, the composition and nature of the embolus from each stroke mechanism was not confirmed pathologically. This may have confirmed our hypothesis.
In conclusion, PFO-stroke was more frequently observed as a single cortical or multiple small scattered lesions and was more often found in the vertebrobasilar circulation, without any visible occlusion by MRA. The recanalization rate was lower than that observed in AF-stroke. These differences in imaging characteristics may help to distinguish the exact mechanisms of cryptogenic stroke and may be useful in considering treatment for secondary prevention.

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Disclosures
None.

References
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SUPPLEMENTAL MATERIAL

Imaging Characteristics of Ischemic Strokes related to Patent Foramen Ovale

Bum Joon Kim, MD1; Hoyon Sohn, MD1; Byung Joo Seon, MD2; Jae-Kwon Song, MD2; Dong-Wha Kang, MD1; Jong S. Kim, MD1; and Sun U. Kwon MD1*

1Department of Neurology, 2Division of Cardiology, Asan Medical Center, University of Ulsan, Seoul, Korea

**Table I**: Ischemic lesion pattern according to the embolic risk of PFO

**Table II**: Size of vessel occlusion according to the embolic risk of PFO

**Table III**: Vascular territory of ischemic lesions according to the embolic risk of PFO
<table>
<thead>
<tr>
<th></th>
<th>Single lesion</th>
<th></th>
<th>Multiple lesions</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cortico</td>
<td>Cortical</td>
<td>Small</td>
<td>Large</td>
<td>Multiple</td>
<td>Confluent</td>
<td>Multi-circulatory</td>
</tr>
<tr>
<td></td>
<td>subcortical</td>
<td>Subcortical</td>
<td>Subcortical</td>
<td></td>
<td>Scattered</td>
<td>+ additional</td>
<td></td>
</tr>
<tr>
<td>Low-risk</td>
<td>12 (20.3)</td>
<td>18 (30.5)</td>
<td>5 (8.5)</td>
<td>3 (5.1)</td>
<td>17 (28.8)</td>
<td>2 (3.4)</td>
<td>2 (3.4)</td>
</tr>
<tr>
<td>Medium-risk</td>
<td>11 (30.6)</td>
<td>12 (33.3)</td>
<td>2 (5.6)</td>
<td>2 (5.6)</td>
<td>5 (13.9)</td>
<td>4 (11.1)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>High-risk</td>
<td>4 (16.0)</td>
<td>11 (44.0)</td>
<td>1 (4.0)</td>
<td>2 (8.0)</td>
<td>5 (20.0)</td>
<td>1 (4.0)</td>
<td>1 (4.0)</td>
</tr>
</tbody>
</table>

Results are expressed in number and percentage (raw).

Embolic risk of PFO is defined as;

- **Low**: PFO size less than 2 mm and without atrial septal aneurysm or hypermobile septum
- **Medium**: PFO size more than 2 mm or with atrial septal aneurysm or hypermobile septum
- **High**: PFO size more than 2 mm and with atrial septal aneurysm or hypermobile septum
Table II Size of vessel occlusion according to the embolic risk of PFO

<table>
<thead>
<tr>
<th>Embolic Risk</th>
<th>Extracranial large artery occlusion</th>
<th>Intracranial main artery occlusion</th>
<th>Intracranial branching artery occlusion</th>
<th>No visible stenosis occlusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-risk</td>
<td>0 (0)</td>
<td>9 (15.3)</td>
<td>11 (18.6)</td>
<td>39 (66.1)</td>
</tr>
<tr>
<td>Medium-risk</td>
<td>2 (5.6)</td>
<td>4 (11.1)</td>
<td>4 (11.1)</td>
<td>26 (72.2)</td>
</tr>
<tr>
<td>High-risk</td>
<td>0 (0)</td>
<td>6 (24.0)</td>
<td>4 (16.0)</td>
<td>15 (60.0)</td>
</tr>
</tbody>
</table>

Results are expressed in number and percentage (raw).

Embolic risk of PFO is defined as:

- Low: PFO size less than 2 mm and without atrial septal aneurysm or hypermobile septum
- Medium: PFO size more than 2 mm or with atrial septal aneurysm or hypermobile septum
- High: PFO size more than 2 mm and with atrial septal aneurysm or hypermobile septum
<table>
<thead>
<tr>
<th></th>
<th>RCC</th>
<th>LCC</th>
<th>VBC</th>
<th>Multi-circulatory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-risk</td>
<td>14 (23.7)</td>
<td>20 (33.9)</td>
<td>23 (39.0)</td>
<td>2 (3.4)</td>
</tr>
<tr>
<td>Medium-risk</td>
<td>8 (22.2)</td>
<td>10 (27.8)</td>
<td>18 (50)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>High-risk</td>
<td>5 (20.0)</td>
<td>8 (32.0)</td>
<td>11 (44.0)</td>
<td>1 (4.0)</td>
</tr>
</tbody>
</table>

Results are expressed in number and percentage (raw).

Embolic risk of PFO is defined as:

- **Low**: PFO size less than 2 mm and without atrial septal aneurysm or hypermobile septum
- **Medium**: PFO size more than 2 mm or with atrial septal aneurysm or hypermobile septum
- **High**: PFO size more than 2 mm and with atrial septal aneurysm or hypermobile septum

RCC: right carotid circulation, LCC: left carotid circulation VBC: vertebra-basilar circulation